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Achieving prescribed gain/frequency responses with advances in hearing aid technology

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Abstract—Technological limitations have restricted the capability of older generation in-the-ear (ITE) hearing aids to closely match prescribed real ear gain/frequency responses. Newer technology, widely available in currently marketed ITE hearing aids, has considerably improved this capability. Data for 60 ears are presented comparing the real ear insertion gain (REIG) actually achieved to the target REIG, using ITE hearing aids having: 1) older generation narrow-band receivers, and amplifiers with single-pole-filter low frequency tone control and a class A amplifier output stage (n = 30), and 2) newer generation amplifiers with a two- or four-pole-filter low frequency tone control, and wide band receivers, containing a class D amplifier output stage (n = 30). With the newer technology ITE hearing aids, the means and ranges of deviation from target gain were reduced. Capability for achieving prescription REIG with ITE hearing aids can be further improved with multichannel amplifiers. Examples of the latter are shown for several difficult-to-fit audiograms.

Key words: *frequency responses, hearing aid technology, in-the-ear hearing aids, real ear gain.*

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INTRODUCTION

Over the past 15 years, numerous prescription formulas for hearing aid fitting have been proposed, each specifying a desired gain/frequency response based on the audiologic test results of a given hearing-impaired patient (1,2). The majority of these formulas use audiometric thresholds and/or suprathreshold loudness judgments in their calculations, with the most common goal that of maximizing audibility of the speech spectrum or of amplifying the speech spectrum to "most comfortable" listening level. Given the current wide availability and use of probe microphone measurement systems, prescriptive fitting of the real ear insertion response (REIR) appears to have largely replaced the traditional, comparative speech approach (3), at least for initial selection of amplification parameters.

Unfortunately, a problem has arisen in the practical application of prescriptive approaches to hearing aid fitting. In-the-ear (ITE) hearing aids, which make up the largest percentage of hearing aids sold today (4), have been reported to be too inflexible to adequately match prescribed gain/frequency responses (5,6). The primary reason for these negative findings to date has been limitations in past hearing aid technology. Recent advances in technology, however, may make closer approximation to prescribed gain/frequency responses possible.

Past Limitations and New Advances in Technology

Two major limitations in hearing aid technology have been additive in causing the limited capability of many older technology single-channel ITE hearing aids to provide a good match to prescribed frequency response:

1. *Older-vintage hearing aid receivers had a primary frequency response peak in the 1600 to 2200 Hz frequency range and inadequate high frequency sensitivity.* The use of these receivers frequently resulted in two problems. First, a large dip was often seen in the REIR in the frequency range of the peak in the real ear unaided frequency response (REUR), usually at about 2800 Hz. Second, there was inadequate high frequency REIR above about 3000 Hz.
2. *Tone controls available had a limited range of variability.* Until recently, most ITE hearing aids had low frequency tone controls comprised of a single-pole highpass filter, primarily because of physical space limitations preventing the packaging of additional capacitors required for more filter poles. These low frequency tone controls were quite limited in their ability to vary the frequency response, having a slope of only 6 dB per octave. For example, it was possible to reduce gain at 500 Hz by only about 10 dB without changing the high frequency gain significantly.

Because of these limitations, a variety of methods were used in the attempt to fine-tune the frequency response of these ITE hearing aids to better match the prescription target. One technique used was to overfit the overall gain of the hearing aid in order to achieve the required high frequency gain and then to rely on varying the low frequency tone control to match the prescribed gain values at low and mid frequencies. However, since the low frequency tone controls had such a limited range, the resulting frequency response often still exceeded target gain in the low and mid frequencies. The desired high frequency insertion gain target was seldom achieved anyway, even with the highest possible overall gain provided. This was especially true for patients with steeply sloping audiograms and for those with hearing loss confined to the high frequencies.

Limited improvement was sometimes obtained with electronic shifting of the peak in the frequency response of the receiver to a higher frequency. This was accomplished by placing an appropriate-value capacitor across the receiver and/or by using a constant voltage rather than a constant-current amplifier output stage. Some hearing aid designers also turned to mechanical/acoustical techniques to increase high frequency gain relative to low and mid frequency gain. These included using a low-cut response microphone and a stepped bore earmold in conjunction with damping in the hearing aid receiver tubing (7). The stepped or flared earmold bore produces a miniature megaphone in order to match the high acoustic source impedance of the receiver to the low acoustic impedance of the ear canal at the high frequencies. When combined with the newer, wider-band receivers, this approach also achieved some improvement in frequency response fitting.

More recent ITE hearing aids that are on the market employ "active" tone controls, consisting of two- or even four-pole filters, having slopes of 12 dB/octave and 24 dB/octave, respectively. These higher-order filters provide much greater flexibility in varying the frequency response. It is now not uncommon to have low frequency tone controls with a 40 dB range at 500 Hz.

In the past, most ITE hearing aids utilized a class A power output stage in the amplifier. Although not directly related to the number of filter poles, hearing aids with a class A output stage are often associated with a narrow-band receiver response and limited tone control flexibility. Many ITE hearing aids currently being produced employ either a class D or class B output stage in the amplifier and a receiver with a wide-band frequency response. These newer hearing aids typically have a primary frequency response peak at about 3000 Hz and provide adequate gain in the high frequencies. Thus, many ITE hearing aids with good insertion frequency responses are associated with amplifiers that have class D and class B output stages.

METHOD

Comparison of Older Versus Newer Technology Hearing Aids

In order to illustrate the degree of improvement seen in frequency shaping flexibility with older versus newer single-channel technology, data are presented here for 30 ears fit with older-technology

ITE hearing aids that used linear, class A amplifiers and relatively narrowband receivers, and 30 ears fit with newer-technology class D amplifiers with wider band receivers. The hearing aids with class A amplifiers (standard linear, from Argosy Electronics, Inc., Minneapolis, MN) used single-pole filters for the low-frequency tone control. Five of the class D amplifiers had low-frequency tone controls comprised of two-pole filters (Argosy Linear Plus®) and the remaining 25 were comprised of four-pole filters (Argosy Manhattan II®). Due to the small sample size for the two-pole class D amplifier, the data are presented as a group. Examination of individual data, however, revealed no apparent difference in results across the two class D devices.

These data were obtained retrospectively from patient files of veterans who received hearing aids at the Department of Veterans Affairs Medical Center in Nashville, TN, and represent, therefore, typical clinical accuracy in routine hearing aid fittings. The data shown for the older technology ITEs were collected in late 1989, and the data shown for the newer technology ITEs were collected in late 1991 by the same two audiologists. Shown in **Table 1** are the mean audiograms, and standard deviations, for the ears fit with newer versus older technology hearing aids. Audiometric configurations within each group ranged from mildly to severely sloping.

The following protocol was used for all fittings. For each ear, desired gain/frequency response was calculated using the NAL-R—revised National Acoustics Laboratories formula (8) and a custom ITE was ordered.[1] With an order, the manufacturer

Table 1.
Means and standard deviations of audiological thresholds for each group of ears.

		Frequency (Hz)						
		250	**500**	**1000**	**2000**	**3000**	**4000**	**6000**
Older	$\bar{x}$	29	29	31	49	63	73	74
technology	(sd)	(14)	(15)	(16)	(20)	(19)	(16)	(17)
Newer	$\bar{x}$	30	33	39	53	63	71	73
technology	(sd)	(13)	(14)	(14)	(13)	(19)	(19)	(21)

$\bar{x}$ = mean
sd = standard deviation

was given only the earmold impression and the prescribed full-on 2 cc coupler gain values. Audiograms were not supplied. To provide maximum flexibility in fitting to prescribed values, each hearing aid was ordered with a tone control and variable venting inserts. In addition, most of the Manhattan II hearing aids had a bandpass trimpot. When a hearing aid arrived from the manufacturer, electroacoustic evaluation was accomplished first to ensure proper functioning (ANSI S3.22 - 1987), then the hearing aid was fit to the patient's ear using probe-microphone measurement of real ear insertion gain (REIG) with a Fonix model 6500 instrument. A broadband composite signal was presented at 70 dB SPL from a loudspeaker positioned 1 meter from the subject at a 45° azimuth. Trimpots and/or venting were adjusted as necessary to achieve the closest possible match to NAL-R prescribed real ear insertion gain (REIG) values at each frequency. For the data presented here, the REIG values obtained were compared to the insertion gain values that had been prescribed, in order to determine the degree of deviation from target.

RESULTS

The means of the 30 prescribed REIGs at each frequency (filled circles), and the means of the 30

[1] It is notable that current prescriptive formula approaches were not specifically developed for use with adaptive-frequency-response (AFR) hearing aids such as the Argosy Manhattan II or K-Amp® (Etymotic Research, Inc., Elk Grove Village, IL). In fact, the prescribed frequency response is an attempt to provide the best compromise when a single, fixed frequency response must be used across multiple listening environments. Unfortunately, however, there is no established approach for the setting of electroacoustic parameters in AFR hearing aids. For our purposes, we chose to set the gain/frequency response of the AFR hearing aids to match prescribed values with a moderate speech-level input (70 dB SPL), on the assumption that adaptive processing will occur at higher and lower input levels.

An argument can also be made for specifying different frequency responses for AFR hearing aids than those prescribed with current formulas. Take, for example, an AFR hearing aid that functions in a manner similar to the Argosy Manhattan II; that is, low frequency gain is reduced as input level increases. The assumptions underlying this approach are that high-level, low frequency energy is more likely to be noise than speech, and that if excessive upward spread of masking occurs in a hearing-impaired ear, it will be reduced. It can be argued that more gain should be supplied in the low frequencies for this type of processor than is currently prescribed, particularly when fitting patients with normal or near-normal thresholds in the lower frequencies. The rationale is that low frequency gain will be sufficiently reduced in high-level noise environments by the adaptive function to provide the above benefits, but that the greater low frequency gain supplied in low-level, quiet environments will actually enhance perceptual sound quality (10). It is clear that further research into the development of appropriate fitting techniques for AFR hearing aids is needed. At present, however, we would encourage the use of broadband stimuli presented at multiple input levels to more fully characterize the functioning of these devices (11). In addition, evaluation of speech recognition in quiet and in noise is important, and adequate follow-up is a crucial factor in assuring user success.

REIGs actually obtained for each fitting (open circles), are shown in **Figure 1a** for the older-vintage hearing aids, and in **Figure 2a** for the newer technology hearing aids. Data at 250 Hz were eliminated from the figures due to noise problems in the real ear measurements at this frequency. Shown in **Figure 1b** and **Figure 2b**, for the older and newer technology ITEs, respectively, are the means and standard deviations of individual deviations from target; that is, the differences between prescribed insertion gain and the insertion gain actually obtained with each hearing aid. A positive value indicates that the gain obtained was greater than that prescribed and a negative value indicates that the gain obtained was less than that prescribed. Linear regression lines and values are also shown in **Figure 1b** and **Figure 2b**.

Note that the older technology hearing aids **(Figure 1)** tended to provide too much gain through the mid frequencies and too little gain in the high frequencies relative to prescribed values, as reflected both in the mean data and in the downward slope of the regression line in **Figure 1b**. In fact, adequate gain was achieved at 4000 Hz in only two of the 30 ears, and too much gain resulted at 1500 Hz in 24 of the fittings.

In contrast, the newer technology hearing aids **(Figure 2)** provided, on average, closer approximations to prescribed REIG across the frequency range. In particular, the flatter regression line, and better fit to the mean data, indicates an improvement in the ability to achieve sufficient gain at 4000 Hz without excessive mid-frequency gain. Smaller standard deviations indicate the reduced spread in the data for newer technology hearing aids.

Another way to measure the central tendency of the data is to examine the number of fittings that fall within an acceptable degree of error from target REIG. We generally consider plus or minus 5 dB from target to be acceptable. **Table 2** lists, for older versus newer technology hearing aids, the percentage of fittings at each frequency in which the REIG actually fit was within ±5 dB of the prescribed REIG. Across mid and high frequencies, a substantially higher percentage of fittings fell within these guidelines for the newer technology ITEs than for the older technology ITEs, again indicating a large improvement in frequency response shaping capability.

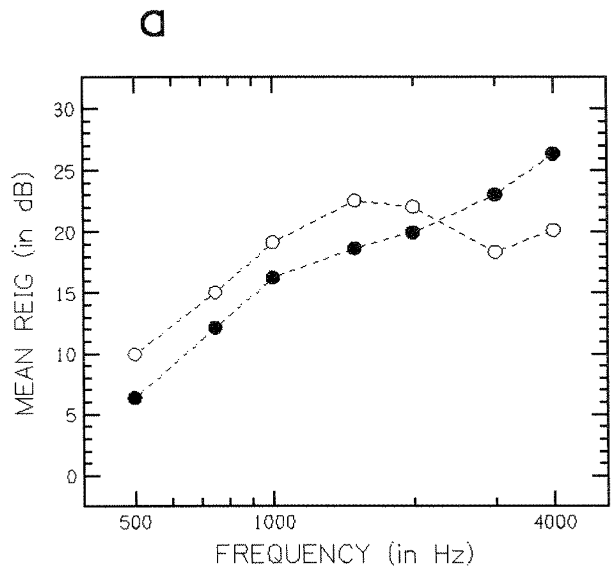

Figure 1a.
Closed circles represent the mean prescribed insertion gain/frequency response, and open circles represent the mean REIG actually achieved, for the 30 older technology ITEs.

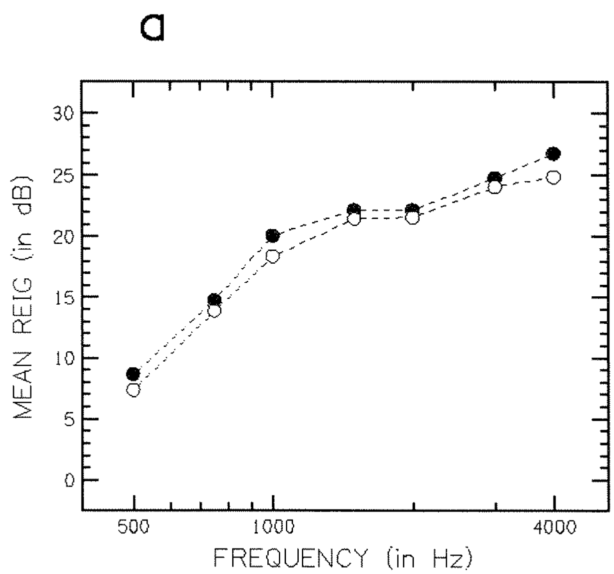

Figure 2a.
Closed circles represent the mean prescribed insertion gain/frequency response and open circles represent the mean REIG actually achieved, for the 30 newer technology ITEs.

Multi-Channel Amplifiers

Historically, most hearing aid amplifiers have been single-channel devices. In order to compensate for the insertion gain dip at 3000 Hz, some

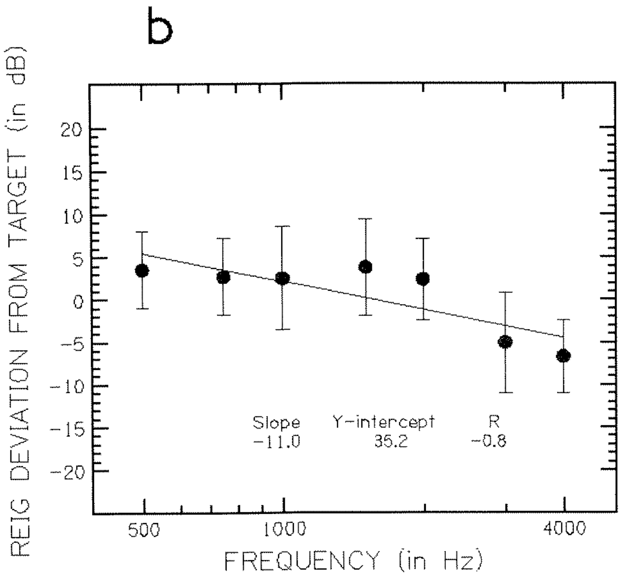

Figure 1b.
The means and standard deviations of individual deviations from target for each of the 30 older technology ITEs (i.e., the differences between prescribed insertion gain and the insertion gain actually obtained). A positive value indicates that the gain obtained was greater than that prescribed and a negative value indicates that the gain obtained was less than that prescribed. The linear regression line is also shown.

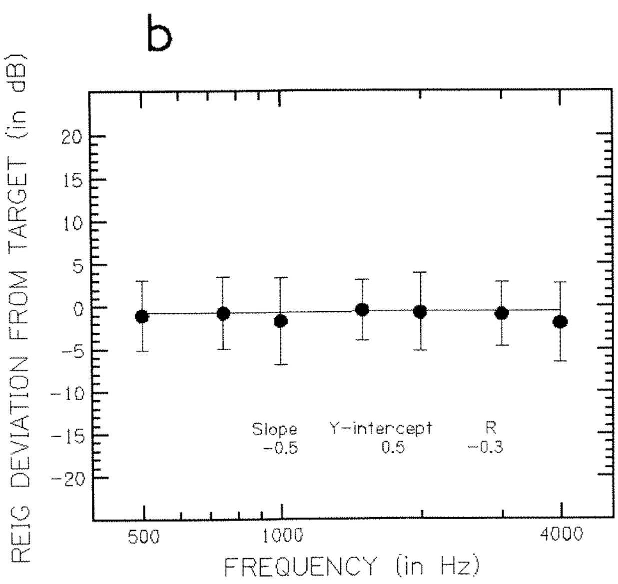

Figure 2b.
The means and standard deviations of individual deviations from target for each of the 30 newer technology ITEs. A positive value indicates that the gain obtained was greater than that prescribed and a negative value indicates that the gain obtained was less than that prescribed. The linear regression line is also shown.

Table 2.
Percentage of ears in each group with deviation from target REIG of plus or minus 5 dB or less.

	Frequency (Hz)						
	500	**750**	**1000**	**1500**	**2000**	**3000**	**4000**
Older technology	67	67	57	70	67	53	40
Newer technology	67	80	77	93	73	83	80

manufacturers have successfully employed a second channel of amplification via an additional bandpass filter to add gain in the 3000 Hz frequency range. An example of this approach is shown in **Figure 3a.** The effect of the second channel on the HA-1 2 cc coupler frequency response is shown in **Figure 3b.** The effect on frequency response measurements in a real ear, obtained with an Acoustimed HA-2000, is shown in **Figure 3c**. A significant increase in mid and high frequency REIG is seen with counterclockwise rotation of the bandpass potentiometer in this ITE hearing aid.

One of the most recent technological advances in hearing aids has been incorporation of a graphic or parametric equalizer within the hearing aid amplifier. Multichannel amplifiers give much finer resolution in frequency response shaping than do single-channel amplifiers. With a graphic equalizer, gain is controllable in each frequency band. With a parametric equalizer, gain is controllable in each frequency band, but, in addition, the crossover frequencies of the bands can be shifted.

The ability to precisely match a prescribed gain/frequency response with multichannel devices greatly exceeds that of older single-channel devices. Three individual examples of matches between measured and NAL-R prescribed REIG with a 3-channel parametric equalizer ITE hearing aid (Argosy 3-Channel-Clock®) are shown in **Figure 4. Figure 4a** illustrates a match obtained for a severely sloping audiogram with normal hearing through 2000 Hz. This audiometric configuration is particularly difficult to fit with single-channel hearing aids because the actual insertion gain achieved will often be less than the target gain prescribed in the high frequencies, and greater than that prescribed in the mid frequencies. **Figure 4b** illustrates the match obtained for an audiogram with a rising configuration.

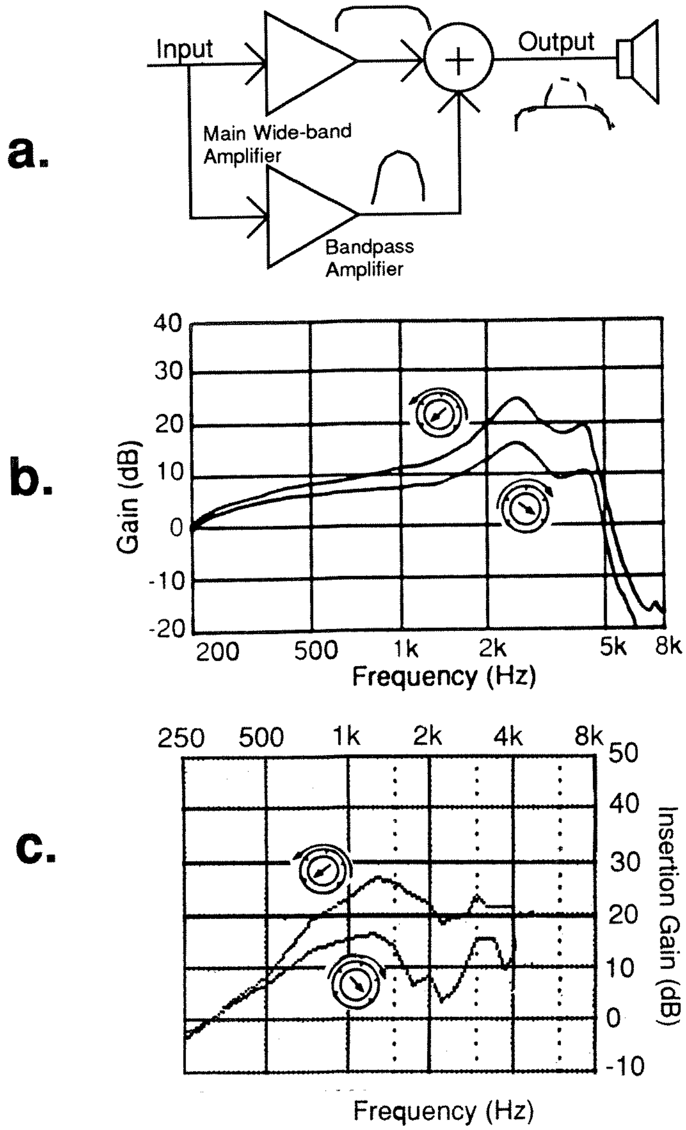

Figure 3.
Figure 3a illustrates an example (Argosy Manhattan II) of the use of an additional amplifier channel with bandpass filter, added to a single-channel amplifier to obtain an increase in gain in the mid to high frequency region. The effect on 2 cc coupler gain of adding the second channel is shown in Figure 3b, and with probe microphone measurement of REIG in Figure 3c.

Finally, **Figure 4c** illustrates a "reverse cookie-bite" configuration; that is, a region of normal hearing in the mid frequencies with hearing loss confined to higher and lower frequencies. For this latter audiogram, it is typically impossible to achieve a reasonable approximation to prescribed gain using single-channel ITE technology, and possible, but difficult, with acoustic earmold or earhook modifications in behind-the-ear hearing aids. Note the accuracy with which the gain/frequency response matched the prescribed REIG for all three cases with the 3-channel parametric equalizer ITE hearing aid.

DISCUSSION

The data shown indicate substantial improvement in the capability of newer technology ITE hearing aids to achieve good approximations to prescribed gain/frequency responses. With two- or four-pole filters for low frequency tone controls, and wide-band receivers with class D amplifier output stages, adequate high frequency gain can be achieved without overamplification of the mid frequencies. Although the hearing aids used in this study were from Argosy Electronics, these technological innovations are also available from other manufacturers and we would expect to see comparable results. The flexibility of the three-band ITE hearing aid with parametric equalization is sufficient to supply an accurate match even with more unusual audiograms that have previously been quite difficult to fit.

This improved flexibility also provides greater opportunity for successful revision of a patient's gain/frequency response, if this is considered desirable after the initial fitting to prescribed values. Because prescriptive formulas are based on mean data for several parameters, the optimal frequency response for an individual patient may in fact differ from the prescribed target. A number of researchers have argued that a prescribed gain/frequency response should be considered only as a "ballpark" starting point in the fitting process, followed by adjustment based on evaluation of speech understanding ability and/or perceptual sound quality, and with follow-up regarding patient satisfaction (8,9). Modifications to the prescribed frequency response for a patient whose speech recognition performance is poorer than expected would typically be in the direction of increased high frequency gain relative to low frequency gain. The data presented here suggest that such modification will be achieved more easily with newer technology than it has been in the past.

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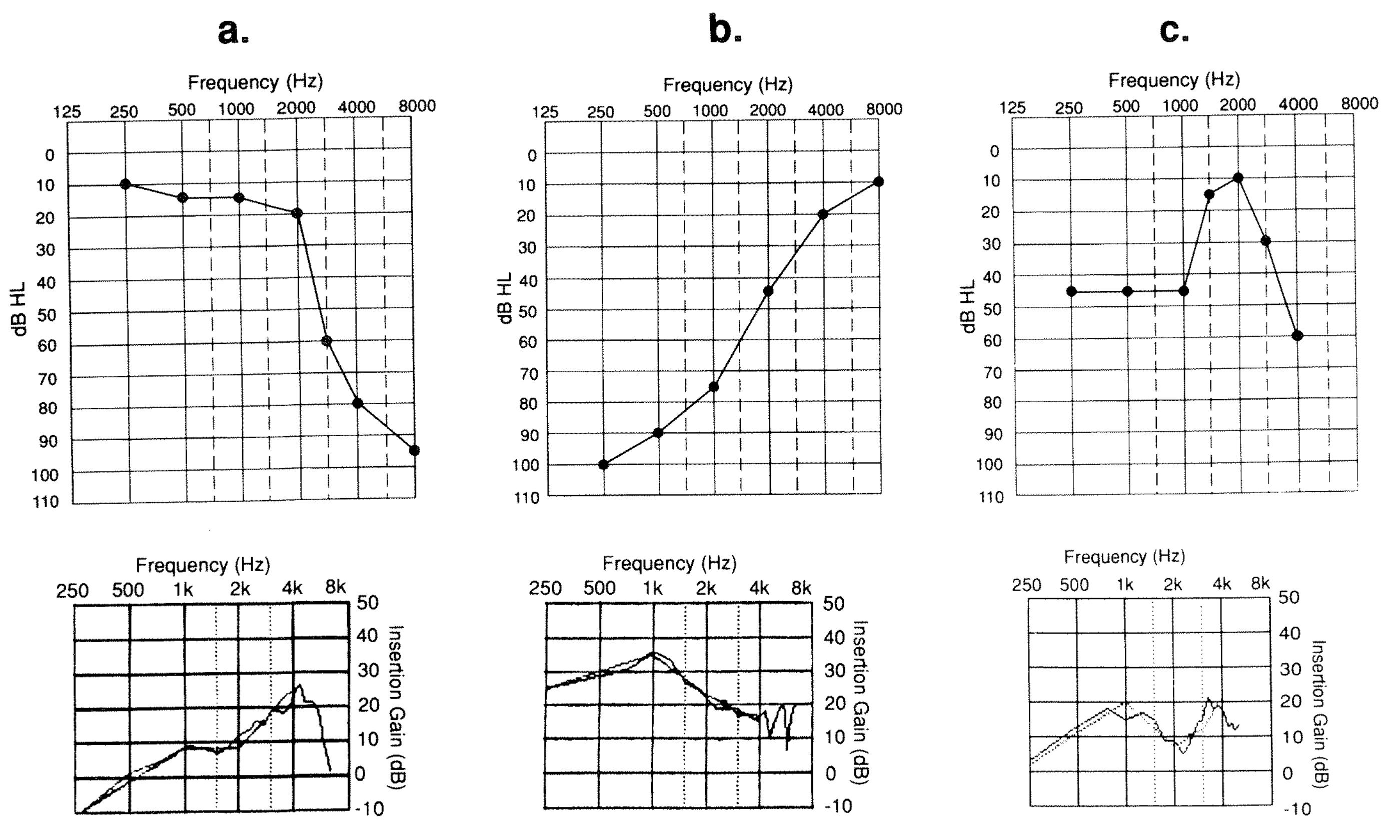

Figure 4.
Three examples of the match to prescribed REIG target obtained with a 3-channel ITE hearing aid with parametric equalization (Argosy 3-Channel-Clock). For each case, the audiogram is shown in the upper part of the figure, and REIG measurements in the lower part of the figure, with the smoother line representing the target insertion gain.

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